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UNITED STATES COAST GUARD EMERGENCY UNDERWATER ESCAPE REBREATHER EVALUATION

By;

C. G. GRAY, LCDR,MC,USN
E. D. THALMANN, CDR,MC,USN
R. SYKLAWER, ENS, USNR

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Submitted by:

C. G. GRAY
LCDR, MC, USN

Reviewed by:

E. D. THALMANN
CDR, MC, USN
Senior Medical Officer

Approved by:

R. A. BORNHOLDT
CDR, USN
Commanding Officer

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The United States Coast Guard (USCG) Emergency Underwater Escape Rebreather (UER) was evaluated at the Navy Experimental Diving Unit. Physiologic testing in the dry laboratory, monitoring breath-to-breath O_2 and CO_2 levels, delineated the factors used in selection of 40% O_2 as an appropriate and safe breathing mixture. Tests during exercise provided the maximum usable duration in cold water to be 2 minutes. Pool studies evaluated the suitability for in-water use of the UER to a maxi-

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ABSTRACT

The United States Coast Guard (USCG) Emergency Underwater Escape Rebreather (UER) was evaluated at the Navy Experimental Diving Unit. Physiologic testing in the dry laboratory, monitoring breath-to-breath O_2 and CO_2 levels, delineated the factors used in selection of 40% O_2 as an appropriate and safe breathing mixture. Tests during exercise provided the maximum usable duration in cold water to be 2 minutes. Pool studies evaluated the suitability for in-water use of the UER to a maximum working depth of 6 FSW. The results demonstrated the UER to be an acceptable shallow depth emergency escape device. The use of a nose clip or face mask is recommended to minimize gas loss and possible aspiration of water through the nose. Minor shortcomings in the breathing characteristics of the device may be improved by changes in the breathing bag configuration.

Introduction

The United States Coast Guard (USCG) Emergency Underwater Escape Rebreather (UER) is an inflatable double bladder life vest intended for use by USCG helicopter crewmen for underwater escape in the event of a downed, capsized aircraft. The UER consists of a rebreathing bag and mouthpiece, a 12 liter oxygen cartridge for the rebreathing gas, and a carbon dioxide cartridge for inflation of a separate floatation compartment. After inflation of the oxygen rebreathing compartment, the crewmen may inhale from and exhale into the rebreathing bag while attempting to escape from the disabled helicopter. Upon successful egress, the second vest bladder can be inflated with the CO_2 cartridge to provide maximal buoyancy.

Previous Coast Guard tests on the UER have shown that rebreathing duration times using 100% O_2 are about 70% higher than when using air. However, a 100% O_2 breathing gas may predispose the individual to sudden blackout from CO_2 build up (1, 2) which could pose a considerable danger. This report describes the first U.S. Navy test of the UER designed to evaluate its maximal breathing duration, the appropriate gas mixture for use in the UER, and the UER's performance as an underwater breathing device.

Method

Testing consisted of both dry laboratory and submerged pool studies using four healthy male U.S. Navy divers in good physical condition. Dry studies were used to determine optimum breathing gas composition and maximum breathing durations. Submerged studies were used to evaluate underwater performance during ergometer exercise, as well as simulated helicopter escape conditions.

Dry Studies:

Dry studies were performed either at rest or during exercise on an electrically braked bicycle ergometer (Collins) at 44, 66, or 93 watts. The oxygen consumption ($\dot{V}_{O_2}$), minute ventilation ($\dot{V}_E$), and CO_2 production ($\dot{V}_{CO_2}$) were measured by collecting two 1-minute mixed expired gas samples during exercise, or one 5-minute sample for subjects at rest, using a Hans-Rudolf one-way valve fitted to weather balloons. Samples were collected after 5 minutes of either rest or exercise to ensure steady state had been attained. The mixed expired samples were then analyzed for gas composition and volume with a Perkin Elmer MGA 1100 Mass Spectrometer and a 120 liter Tissot spirometer with $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ calculated using standard equations. A continuous gas sample was taken from the mouthbit at 60 cc min^{-1} and analyzed by the mass spectrometer and the breath-by-breath O_2 and CO_2 levels recorded on a strip chart recorder.

For each test, the UER was filled with 12 liters of one of four gases (AIR, 40% O_2/60% N_2, 50% O_2/50% N_2, or 100% O_2). The subject started breathing on the UER immediately after the steady state $\dot{V}_{O_2}$ gas collections were completed, and continued respiring into the rebreather until they or the supervising Medical Officer deemed termination necessary. Upon termination, the UER bag was sealed and the remaining gas well mixed. This mixed rebreathing bag sample (F_MO_2 or F_MCO_2) was then analyzed for volume and composition as previously described. The subjects were instructed to start and end the test at the end of a normal expiration (FRC). Additionally, during the 93 watt steady-state exercise breathing air, the maximal voluntary breath-hold time was measured.

Pool Studies:

The subject wore the UER inflated with 12 liters of the 40% O_2/60% N_2 breathing gas chosen from the dry study results. No instrumentation was used to monitor the UER during the actual pool tests.

For the first submerged test, the subject entered the water and pedalled on a horizontal underwater ergometer at 66 watts (equivalent to 90 watts dry (3) while breathing from a SCUBA regulator and wearing a face mask. After pedalling for 5 minutes at a maximum depth of 2 FSW, the subject quickly changed to re-breathing from the UER and removed the face mask. The subject continued the timed exercise as long as he felt he could. After each test, the UER gas volume and composition was determined as previously described.

In the second portion of the pool study, the subject, wearing the inflated UER and a face mask, entered the water and initiated UER rebreathing. The subject immediately descended below a metal grate to a depth of approximately 5 FSW and moved around under the grate to simulate a submerged escape. He surfaced when feeling uncomfortable or when signaled by topside. During this portion of the test, human factors evaluations were performed to assess ease of breathing and the ability to effectively maneuver under the grate during the escape simulation.

Results

The $\dot{V}_{O_2}$ of all four subjects measured at the dry test work rates is given in Table 1, agreeing with previously measured oxygen consumption data (3). Table 1 presents the averaged results from all dry experiments performed. The breathing durations at 93 watts ($\dot{V}O_2$ 1.7 l/min) on 100% O_2 and

40% O_2 were 142 $\pm$ 21 and 123 $\pm$ 5 seconds respectively. The one run using 50% O_2 gave a duration of 133 sec and the mean duration on air was 74 sec. The mean maximal voluntary breath-hold time while working at 93 watts was 24.6 ($\pm$ 6.0) seconds. The final inspired CO_2 levels (F_ICO_2) for the 100, 50 and 40% O_2 mixtures were nearly equal (11.9, 11.4, and 11.4 respectively) while the final O_2 level (F_IO_2) varied, being 13% for the 40% O_2 mix, 23.3% for the 50% O_2 mix, and 65.2% for 100% O_2.

For all rebreathing studies, some degree of dyspnea started in the early stages of each test. With AIR, this dyspnea was pronounced in the early stages and progressed rapidly to extreme dyspnea and voluntary termination with subjects exhibiting cyanosis. This was a result of the extremely hypoxic inspired O_2 levels present at the end of exercise. Recovery after termination of rebreathing was rapid after the AIR studies. When using 100% O_2, the subjects exhibited a delay in onset of dyspnea which progressed more slowly and was of a lesser severity than that experienced using AIR. In the later stage of the 100% O_2 tests, the subjects related marked confusion, mild euphoria relieving some of the dyspnic effect, more prominent vertigo and, in two cases, near syncope. One subject related he "forgot how to stop". All four subjects agreed that with 100% O_2 they would have continued rebreathing on the UER had the test not been involuntarily terminated by the Medical Officer because of symptoms of severe CO_2 intoxication. Vertigo, mental confusion, headaches and, in one case, muscular twitching for 10 minutes past termination were the most prominent neuromuscular symptoms experienced while using 100% and 50% O_2. The one subject who breathed the 50% O_2 mix related no subjective difference between 50% and 100% O_2. When using 40% O_2, the subjects related a more pronounced dyspnea and increased mental awareness near the trial termination. Figure 1 shows the plateau of breathing duration times achieved by increasing the 0_2% in the breathing mixture.

Referring to Table 1, using the initial gas concentration (F_o), the final end inspired gas concentration (Final F_I0_2 or F_ICO_2), the Final mixed gas concentration (F_M0_2 or F_MCO_2) and final Volume (V_F), the effective ventilated UER bag volume (V_{EV}) can be calculated by the formula:

$$V_{EV} = \frac{(F_o - F_M)}{(F_o - \text{Final } F_I)} (V_F)$$

Listed in column 9 of Table 1 are the average of V_F, V_{EV} and the percent of total bag volume (%Vo) each represents. The overall mean effective ventilated bag volume is calculated to be 86% $\pm$ 6% of the total volume (approximately 10.3 1).

The results of the in-water ergometer studies are listed in Table 2. The subjects complained of water leakage and gas loss through the nose during the trial. The average duration of 97 $\pm$ 19 seconds was shorter than the corresponding dry study time of 123 $\pm$ 5 seconds, which the subjects felt could have been prolonged excepting the water and gas leakage experienced.

Table 3 lists the data for the submerged escape simulation. The water and gas leakage problem experienced during the submerged ergometer studies was eliminated by wearing a SCUBA face mask. The times recorded were greater (119 $\pm$ 15 sec) than for the ergometer study with the subjects operating at a substantially lower work rate and all subjects felt they could have stayed submerged longer if sufficiently motivated.

Initial human factors evaluations revealed inadequacies in design that have been improved to achieve the current approved version. The difficulties noted required both hands to control the UER mouthbit and bags, severely impeding the simulated escape efforts. These problems were: (1) weakness of mouthbit valve, allowing inadvertent closure while in use, that required one hand to hold the valve open; (2) excessive elasticity of the mouthpiece rubber, causing the mouthbit to pull partially out of the mouth and allowing gas to escape from the bags; (3) inadequate jocking of the vest and bags to the body, allowing the bags to float up into the diver's face thereby obstructing visibility; and (4) certain diver underwater orientations forced the air away from the breathing port side of the bag, causing occlusion of the breathing port during inhalation. The problem of the bag collapsing against the breathing hose port, although improved, continues to produce a considerable increase in breathing resistance in the left-side-down position.

Discussion

It is presumed that downed helicopters will land in cold water, and the viability of the UER as an effective escape device is tested according to this worst case assumption. The steady state $\dot{V}O_2$ measuring techniques used for this evaluation provide a realistic gauge of the operational UER breathing duration time. An individual suddenly immersed in cold water will attain a $\dot{V}O_2$ of three times the resting value, about $1.2 \ell \cdot min^{-1}$ (4, 5), within the first two minutes of submersion. This increase, added to the activity of escape efforts, will elevate the $\dot{V}O_2$ to $1.5\ \ell \cdot min^{-1}$ or greater. The dry ergometer work rate of 93 watts closely approximates this value yielding an average $\dot{V}O_2$ of $1.7\ \ell \cdot min^{-1}$.

Previous helicopter deaths have been mainly from drowning in cold water crashes. This may be from the involuntary exhalation and hyperventilation secondary to sudden cold water immersion (5). A trained and well-controlled individual may be able to overcome these involuntary reflexes. However, the average breath-hold time of 24.6 seconds at 1.7 $\ell \cdot min^{-1}$ $\dot{V}_{O_2}$, agreeing with previous data (6), is assumed to represent the actual maximum voluntary apneic (breath-hold) period under these conditions. This short time is probably inadequate to allow escape, even if the crewmen could sustain the apnea. Hyperventilation will not affect the UER breathing duration times which is dependent only on O_2 consumption (and CO_2 production), and is independent of minute ventilation, tidal volume or respiratory rate.

The data in Table 1 shows the trade-off between hypoxia and hypercapnia as the driving force for voluntary termination. Using air, the hypoxic drive predominated, accompanied by extreme dyspnea and air hunger. While breathing 100% O_2, the hypoxic drive was suppressed leaving only the hypercapnia to cause termination of rebreathing. Removing the hypoxic drive caused the subjects to continue rebreathing well beyond the point where their mental state would be adequate for effective helicopter egress. Thus, the extra breathing duration time gained using 100% O_2 only served to allow escapees to overstay their useful time in the water and may even result in drownings from hypercapnic blackouts. The 40% O_2 mix, while shortening the rebreathing time, provides an extremely strong stimulus for surfacing while mentation is still relatively clear, ensuring that escapees will not overstay their submerged time. The UER using the 40% O_2 breathing mix yields a working duration of 118 seconds (123 seconds minus one standard deviation). According to Coast Guard personnel, this time is more than adequate for the escape procedure. This breathing duration would be expected to be longer in warm water. Thus, the 40% O_2 mixture, while providing adequate duration, also provides a warning, via the hypoxic drive mechanism, of the impending CO_2 intoxication.

Breathing on any underwater breathing apparatus without occluding the nostrils adds a level of difficulty to any diving situation. One of the difficulties to be mastered by diving candidates is the adjustment to such an urgent situation and usually requires considerable training. The use of the UER without either a nose clip or face mask (covering the nostrils) invites water intake and gas loss through the nostrils. This adds to the drowning danger for use in an emergency and may severely decrease duration time through inadvertently expelling gas. As observed during developmental testing, loss of gas may produce a severe ventilatory restriction due to partial occlusion of the breathing port by the collapsed bag. Depending on the diver's orientation and amount of gas lost, the severity of this ventilatory restriction could increase. Since individuals using the UER will probably not be experienced divers and since conscious prevention of water aspiration or gas elimination through the nose during escape situations will be difficult, a noseclip or face mask covering the nose should be used with the UER.

The final approved version of the UER incorporates a firm rubber mouthpiece mated to a positive locking (open or closed) valve, a jock strap to hold the UER down on the body and a breathing port occlusion prevention device. These improvements allow the escapee full use of hands and the ability to direct his efforts toward escape, rather than requiring attention to maintain control of the UER. However, the bag configuration does not provide for maximal efficiency and safety in practical use of the UER.

In summary, the UER has the capability of providing approximately two minutes of breathing time to a downed helicopter crew member during the escape procedure in worst case conditions. The UER is an adequate emergency escape device to be used only in escape emergencies and in controlled training. A 40% O_2 breathing gas provides the best combination of breathing duration and safety. The use of a noseclip or face mask covering the nose will minimize gas loss and possible aspiration of water through the nose. Alteration of the breathing bag configuration to a standard horsecollar type and inclusion of a device to prevent collapse around the rebreathing hose may substantially improve the practical operating characteristics and safety of the UER.

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WORK RATE (Watts)	GAS MIX ($\%O_2$)	$\dot{V}_{O_2}$ ($l.min^{-1}$)	BREATHING DURATION (Sec)	FINAL $\%CO_2$ (F_ICO_2)	MIXED $\%CO_2$ (F_MCO_2)	FINAL $\%O_2$ (F_IO_2)	MIXED $\%O_2$ (F_MO_2)	FINAL VOL (V_F)/ EFFECTIVE FOL (V_{EV})/%Vo	NUMBER OF RUNS
Rest	Air	$.37 \pm .026$	265 ± 39	$7.3 \pm .8$	5.47 ± 2.02	$9.1 \pm .21$	12.2 ± 5.0	10.2/7.59/.74	4
44	Air	$1.03 \pm .039$	131 ± 12	$8.4 \pm .4$	$7.58 \pm .28$	$6.3 \pm .9$	$7.7 \pm .8$	9.2/8.31/.90	4
66	Air	$1.18 \pm .12$	112 ± 22	$8.2 \pm .7$	$7.15 \pm .74$	7.2 ± 1.6	8.9 ± 1.6	10.4/9.1/.87	5
93	Air	$1.66 \pm .88$	74 ± 9	$8.3 \pm .5$	$7.43 \pm .47$	6.8 ± 1.3	8.9 ± 1.1	10.6/9.26/.87	4
93	40	$1.66 \pm .88$	123 ± 5	$11.4 \pm .5$	10.00 ± 52	13 ± 1.4	16.7 ± 1.1	9.0/7.83/.87	4
93	50	$1.66 \pm .88$	133	11.4	10.73	21	23.3	9.3/8.66/.93	1
Rest	100	$.37 \pm .26$	495 ± 59	$10.6 \pm .5$	$10.14 \pm .57$	62 ± 8.5	74.6 ± 12.8	10.3/8.37/.81	3
66	100	$1.18 \pm .12$	225 ± 58	11.5 ± 1.1	10.67 ± 1.54	60 ± 3.9	66 ± 2.9	7.3/6.49/.89	4
93	100	$1.66 \pm .88$	142 ± 21	$11.9 \pm .8$	$10.33 \pm .26$	55.5 ± 6.4	65.2 ± 5.1	6.6/5.45/.83	4

TABLE I: SUMMARY OF MEAN DATA FROM DRY STUDIES FOR ALL SUBJECTS ($\pm$ STANDARD DEVIATION).

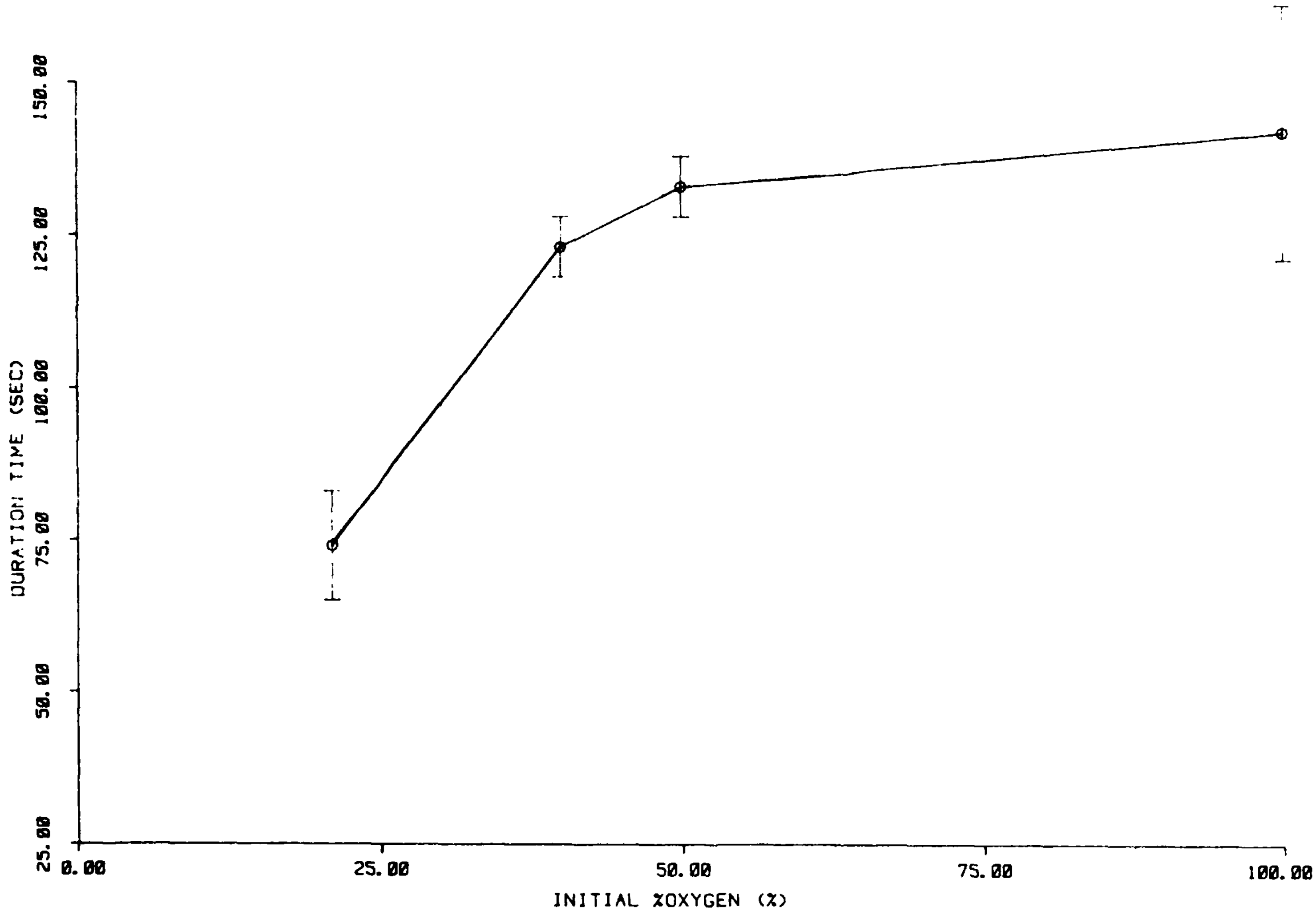
TRIAL	TIME (Sec)	FINAL O_2 F_MO_2 (%)	FINAL O_2 P_{O_2} (mmHg)	FINAL CO_2 F_MCO_2 (%)	FINAL CO_2 P_{CO_2} (mmHg)
1	123	21.3	162.1	7.88	60.0
2	95	21.4	162.8	6.28	47.8
3	94	23.3	177.3	6.85	52.1
4	77	27.7	210.8	5.18	39.4
Mean	97 ± 19.0	23.4 ± 2.99	178.2 ± 22.8	6.55 ± 1.13	49.8 ± 8.59

TABLE 2. INDIVIDUAL DURATION TIMES AND FINAL GAS COMPOSITIONS DURING EXERCISE AT 66 WATTS IN 2 FSW AT A TEMPERATURE OF 31°C.

TRIAL	TIME (Sec)	FINAL O_2 F_MO_2 (%)	FINAL O_2 P_{O_2} (mmHg)	FINAL CO_2 F_MCO_2 (%)	FINAL CO_2 P_{CO_2} (mmHg)
1	140	27.7	210.8	5.86	44.6
2	122	21.3	162.1	7.66	58.3
3	111	24.9	189.5	5.42	41.2
4	105	----	----	----	----
Mean	119 ± 15	24.6 ± 3.20	187.5 ± 24.4	6.31 ± 1.19	48.0 ± 9.05

TABLE 3. INDIVIDUAL DURATION TIMES AND FINAL GAS COMPOSITIONS FOR THE SUBMERGED ESCAPE SIMULATION TEST AT 31°C AND 5 FSW.

FIGURE 1: DURATION TIME VS % O_2 PERFORMED AT 93 WATTS.



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